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FINAL REPORT
MITIGATION INVESTIGATION AND FEASIBILITY STUDY INCLUDING INTERIM REMEDIAL MEASURES
POWERINE OIL REFINERY
SANTA FE SPRINGS, CALIFORNIA

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1.0 INTRODUCTION

This report presents the results of Conceptual and Mathematical Modeling of the unconfined upper aquifer at the Powerine Refinery (Site), located at 12354 Lakeland Road, Santa Fe Springs, California (Figure 1). A program of interim remedial measures has been recommended, based on the modeling results, to hydrodynamically control off-site migration (if any) of the dissolved hydrocarbon plume. Off-site monitoring well locations have also been recommended based on mathematical study of potential solute migration patterns. In addition, a field program to aid in the design of long term remedial practices is outlined.

1.1 BACKGROUND

In February 1985, the California Regional Water Quality Control Board, Los Angeles Region (RWQCB) issued Order No. 85-17 to Powerine Oil Company (Powerine) to "conduct a subsurface investigation of the Powerine Refinery to detect and assess any ground-water pollution which may be present". Powerine retained International Technology Corporation (IT) to conduct the investigation. IT performed the investigation and prepared a report, "Investigation and Site Assessment for Subsurface Contamination" (IT, January 1986).

The report of the investigation was reviewed by the RWQCB and was found "essentially in compliance with the requirements of the order", as stated in a RWQCB letter to Powerine on February 14, 1986. Because the results of the investigation indicated presence of dissolved hydrocarbons in the ground water, the RWQCB requested a mitigation plan, a timetable to correct the situation at the refinery, and quarterly sampling and chemical analyses of the existing wells.

IT prepared a work plan entitled "Mitigation Investigation and Feasibility Study for Ground Water, Powerine Oil Refinery, Santa Fe Springs, California", which was submitted to Powerine and subsequently to the RWQCB in April 1986. The RWQCB reviewed and approved the work plan. However, the RWQCB requested that the possibility of off-site migration of a fuel hydrocarbon plume in the vicinity of the southwest section of the Site also be investigated.

On May 6, 1986, a meeting was held at the regional office of RWQCB in which representatives of the RWQCB, the Department of Health Services (DOHS), Powerine, and IT participated. In that meeting it was agreed by all parties that Powerine and IT pursue the work plan as written and the results of the computer modeling would be used to estimate the possible extent of the plume. Based on the modeling results, a decision would be made regarding the off-site investigation including ground-water monitoring well drilling and sampling, if needed. This report will address these issues. The parties also agreed that Powerine and IT submit bi-monthly progress reports to the RWQCB to inform the agencies about the progress and findings of the investigation.

1.2 SITE HISTORY AND PREVIOUS INVESTIGATIONS

The refinery has been in operation from the late 1930's until July 1984, at which time the refinery operation was shut down except for some product storage and maintenance of existing equipment. The refinery processed crude oil and raw naptha as feed stock to produce gasoline, diesel, and jet fuel. The liquid products were stored at the Site in labeled tanks, ranging in size from 1,000 to 100,000 barrels and were transported via pipeline or truck. Plans are underway to restart the refinery operation in the near future.

As shown in Figure 2, several leaks from above ground storage tanks at the Site have been tentatively identified. The locations of underground structures which may potentially have leaked are also shown in Figure 2. During an accident in 1963, gasoline and water were reported to be ponded on the ground in the area of monitoring well MW-102 while gasoline burned for a few days. The tanks were removed after the fire.

Since 1985, IT investigations have included drilling 11 soil borings (designated as 301 through 309, and 401 and 402, Figure 2) and installing 14 ground-water monitoring wells (designated as MW-101 through MW-104, MW-201 through MW-206, and MW-501 through MW-504, Figure 2). Soil and ground-water samples have been collected and analyzed. In addition, the physical parameters of the upper aquifer were investigated by performing aquifer tests. The results of these investigations have been discussed in detail in the following IT reports:

- Investigation and Site Assessment for Subsurface Contamination (Report, January 1986), and
- Mitigation Investigation and Feasiblity Study for Ground Water (Progress Reports July 11, 1986; August 28, 1986; and November 13, 1986).

The results of the chemical data collected at the Site have indicated areas of soil contamination and ground-water contamination in the uppermost aquifer at the Site. This contamination consists primarily of fuel hydrocarbons and related dissolved organic constituents. The results of the investigations have indicated possible off-site migration of a dissolved hydrocarbon plume.

A summary of the relevant field data collected on the Site hydrogeology is presented in Section 2.0. Section 3.0 discusses the distribution of chemicals in soil and ground water at the Site based on analytical results to date.

1.3 OBJECTIVES AND SCOPE OF WORK

The overall objective of the investigation has been to detect and evaluate soil and ground-water contamination that may be attributed to Powerine operations. The specific objectives of this phase of the investigation are, as follows:

- Further characterization of the hydrogeology of the unconfined upper aquifer with Conceptual and Mathematical Modeling based on the field data collected to date

- Optimization of future monitoring well locations in the unconfined upper aquifer based on the study of potential plume migration patterns

- Analysis of interim remedial measures to remediate possible source areas and control possible off-site migration of contaminants.

To achieve these objectives, a review was performed on all available Site-specific data. This fragmented knowledge of the upper aquifer system was integrated into "Conceptual Models". These Conceptual Models are simplified representations of the real upper aquifer system. "Mathematical Models", in the form of a set of accepted mathematical equations, were then formulated based on these Conceptual Models of the upper aquifer. The technical approach is discussed in more detail in Section 1.5.

These Mathematical Models of the upper aquifer have been solved by both analytical and numerical methods. The ease of application has made an analytical solution the practical first solution technique when studying the upper aquifer. However, a number of assumptions and simplifications regarding the ground-water system are necessary to obtain an analytical solution. On the other hand, the numerical solutions provide a more detailed analysis of the upper aquifer system, but require more precise and a considerably larger amount of data.

These resulting Models of the upper aquifer were then manipulated and the results of these manipulations were used to make decisions regarding the operation of the real aquifer system. This knowledge was evaluated and used to achieve the three objectives of this report.

1.4 STUDY AREA

This phase of the investigation is concerned with the unconfined upper aquifer underlying the Site and possible downgradient areas effected by potential off-site migration, collectively referred to as the Study Area (Figure 3). This aquifer is believed to be underlain by a silty clay which was encountered in most of the borings at the Site and several off-site locations.

1.5 TECHNICAL APPROACH AND REPORT ORGANIZATION

Initially, the field data, collected to date, was analyzed to gain an understanding of the aquifer system. The field data consists of sets of water quality and water level data plus aquifer tests and well logs. These data have been presented in previous IT reports and progress reports.

The hydrogeology of the upper aquifer was first analyzed. Conceptual Models of the upper aquifer system were constructed based on the collected field data. Mathematical Models utilizing the numerical solution technique were formulated based on the Conceptual Models. During the calibration process, the behavior of these Mathematical Models was studied in comparison to the known behavior of the real upper aquifer system.

The possible patterns of solute migration were studied after understanding the ground-water flow regime of the upper aquifer system. These patterns were analyzed in relation to the known source history of the Site and the water quality data. Benzene was selected as the indicator parameter for evaluation and modeling of solute migration. Conceptual Models were constructed based on several possible scenarios for the migration of benzene into the upper aquifer system. Mathematical Models formulated from these Conceptual Models were analyzed analytically and numerically. Monitoring well locations and further investigation of soil conditions were recommended based on these analyses.

The Models were used to evaluate the effect of various interim remedial measures to control possible off-site migration of contaminants. The measures included extraction of contaminated ground water from the upper aquifer to create a hydrodynamic barrier to off-site migration. Extraction programs were simulated with the refined numerical Mathematical Model and a preliminary design with a recommended field program was developed.

Any modeling application inherently involves limitations and uncertainties. In every step of modeling, from conceptualization to calibration of the Mathematical Model, a number of assumptions and approximations are involved. It should, therefore, be emphasized that the Conceptual and Mathematical Models presented in this report should be viewed as a best representation of the real aquifer system's behavior. Refinement of the Models is anticipated with the collection of additional field data through time. However, the Models satisfactorily fulfill the objectives of this phase of investigation.

The methodology and the results of each of these technical activities are discussed in this report. The remaining sections are organized as follows:

- 2.0 Hydrogeology of Upper Aquifer
- 3.0 Solute Migration Patterns of Upper Aquifer
- 4.0 Interim Remedial Measures
- 5.0 Summary and Conclusions

2.0 HYDROGEOLOGY OF UPPER AQUIFER

The hydrogeology of the unconfined upper aquifer within the Study Area was evaluated based on the data collected to date. These data have been presented in previous IT reports and progress reports. Sections 2.1 and 2.2 present a discussion of these data. Conceptual and Mathematical Models of this upper aquifer system are presented in Section 2.3.

2.1 REGIONAL HYDROGEOLOGY

A discussion of the regional hydrogeology of the Study Area was presented in the January 1986 report (IT, 1986). This discussion was based on Bulletin No. 104 of the California Department of Resources (DWR) published in 1961. A summary of this information is presented below.

The Study Area lies within the Santa Fe Springs Plain subgeomorphic province. This plain is a low, slightly rolling topographic feature with the general surface sloping gently northward and southward on either side of the northwest trending Santa Fe Springs anticline. This anticline traverses the central part of the City of Santa Fe Springs.

The Lakewood Formation of upper Pleistocene Age underlies the surface of the plain. This formation consists of alluvial interbedded stream sediments from the San Gabiel River and fan deposits from the Puente Hills. The San Pedro Formation of lower Pleistocene Age underlies the Lakewood Formation and consists of continental sands and silts with gravel beds and interbedded marine clays and muds. Pre-Pleistocene Age marine and non-marine consolidated sediments lie unconformably on crystalline basement rock. The Lakewood and San Pedro Formations have a combined thickness ranging from 700 to 1,100 feet in the Santa Fe Springs area.

Several regional water-bearing units have been identified in the Lakewood and San Pedro Formations. The major water-bearing unit of interest to this investigation is the upper aquifer unit in the Lakewood Formation which literature refers to as the Exposition aquifer. The materials of the Exposition aquifer consist of coarse gravels to clays. The depositional environment of the aquifer material has formed interbedded permeable coarse-grained, and less permeable fine-grained stratigraphic units. Lenticular sand and gravel units are also found within this aquifer creating a complex stratigraphic sequence. The Exposition aquifer is separated from a deeper water-bearing horizon by an unnamed aquiclude. The ground-water levels underlying Santa Fe Springs slope in a southwesterly direction and vary from approximately 80 to 100 feet below ground surface.

2.2 STUDY AREA HYDROGEOLOGY

2.2.1 Stratigraphy

The stratigraphy of the unconfined upper aquifer underlying the Study Area is derived from research of the regional hydrogeology, logs of wells installed by IT at the Site, and driller's logs of wells located within 10,000 feet of the Site. The driller's logs were collected from the Los Angeles County Flood Control District. The January 1986 report (IT, 1986) presented three cross sections based on the interpretation of 10 monitoring well logs and 11 soil borings which portrays the stratigraphy of the area underlying the Site. An August 1986 progress report presented four additional well logs which further detailed the stratigraphy of the southern-most portion of the Site.

This data indicates the unconfined upper aquifer underlying the Study Area is composed of interbedded units of very permeable sand and gravel, permeable fine- to medium-grained sand, and less permeable silty clayey sand. Very permeable lenticular units of sand and gravel with cobbles have also been identified. This upper aquifer extends from approximately 80 to 90 feet below ground surface to an underlying aquitard. This aquitard immediately underlying the upper aquifer is a sandy silty clay zone which has been consistently identified in on-site and off-site well logs at a depth of approximately 100 to 117 feet below surface.

2.2.1.1 Site Stratigraphy

Detailed analysis of the stratigraphy of the upper aquifer at the Site indicates significant changes in the aquifer material and thickness between three major areas moving north to south across the Site. These three major areas include:

- The northern-most third of the Site, extending to the east-west Site boundaries and approximately 600 feet south of the northern Site boundary at well MW-204,
- The central third of the Site, extending to the east-west Site boundaries and approximately 600 feet south of well MW-204, and
- The southern-most third of the Site extending to the east-west Site boundaries and approximately 400 feet north of the southern Site boundary.

Fine-grained deposits predominate in the upper aquifer in the northernmost third of the Site (Figure 2). The total thickness of the unconfined upper aquifer is approximately 15 feet in this region. A very stiff clay layer was encountered at an approximate depth of 100 feet below surface in this area.

The well logs indicate the stratigraphy of the upper aquifer in the central third the Site Area is complex. A fine- to medium-grained sand is indicated in the western and central area of this middle third. This fine- to medium-grained sand unit changes to the east to a silty clayey sand with thin interbedded units of clay. A thick cobble horizon of approximately 15 feet was encountered in the central area at the boring of monitor well MW-504. The thickness of the unconfined aquifer in this middle third ranged from approximately 6 to 28 feet. A sandy silty clay layer was encountered at approximately 117 feet below the ground surface.

The stratigraphy of the upper aquifer in the southernmost third of the Site is also complex. A fine- to medium-grained sand was encountered in the western and central area of this southern third. A gravel horizon was noted in the boring logs of the central portion of this area. The thickness of the unconfined upper aquifer in this southern third of the Study Area presumably ranges from 20 to 24 feet.

In summary, the stratigraphy of the Site is complicated with changes in aquifer material both laterally and vertically across the Site. A discontinuous gravel channel may be present extending from well MW-504 to MW-502. The thickness of this upper aquifer varies from 6 to 28 feet with a bottom layer of sandy silty clay.

2.2.1.2 Off-Site Stratigraphy

The data available to date specifically on the off-site upper aquifer underlying the Study Area (Figure 3) consists of several well logs within 1,000 feet south of the southern boundary of the Site. A well log near the Metropolitan State Hospital indicates saturated sand and gravel from 96 to 115 feet below land surface and a clay layer extending from 115 to 127 feet below land surface. A well log approximately 300 feet to the east of the Hospital indicates a clay layer from 100 to 116 feet below land surface with a sand layer above the clay layer.

2.2.2 Physical Properties of the Aquifer

In July 1986, a series of aquifer tests were performed in the upper aquifer to evaluate its hydraulic properties. Instantaneous discharge (slug) tests, single- and multiple-well pump tests were completed. Details of these aquifer tests were presented in the August 1986 IT progress report. Table 1 summarizes the results of these tests. The transmissivities calculated from both the slug and pump tests ranged from 124 gallons per day per foot (gpd/ft) to 13,613 gpd/ft. Theses transmissivity values are relatively low, indicating that the upper aquifer is not suitable for water supply purposes. According to Freeze and Cherry (1979), transmissivities greater than 100,000 gpd/ft represent good aquifers for water well exploitation.

The single- and multiple-well pump tests indicated a boundary effect. This boundary effect may be the result of several phenomena. The stratigraphy of the Study Area suggests this effect may be the result of a significant change in the transmissivity of the aquifer materials within the influence of the pumped wells. Transmissivity values decreased approximately one order of magnitude after a couple of hours of pumping in wells MW-502, MW-503, and MW-504 (Figure 2).

In summary, these results indicate a heterogeneous aquifer. The transmissivity values correlate closely to the values which might be anticipated based on the well logs discussed previously. The high values of transmissivity correlated to those wells whose stratigraphic logs indicated horizons of sand and gravel. However, the aquifer tests in these wells indicated boundary effects and the transmissivities dropped significantly within a couple hours. This phenomenon may indicate these sand and gravel lenses are very limited in extent.

The lower values of transmissivity correlate to those wells which are perforated in a zone of sandy silt with some clay. The exception to this correlation is indicated by the results of the single well test which was performed in monitoring well MW-503. A very low value of transmissivity (962 gpd/ft) was obtained, although the well log indicates the well is perforated in a zone of sand and gravel. The unexpectedly low value may indicate either a very low well efficiency or this zone of sand and gravel is very limited in extent.

The specific yield was calculated based on the data from a multiple well pump test at monitor well MW-504. This calculation resulted in a range of values from 0.037 to 0.051. These values are reasonable and within the typical range for an unconfined aquifer.

2.2.3 Ground-Water Conditions

Ground water was encountered in all the monitoring wells at the Site at depths ranging between 80 and 90 feet below the land surface. The measurements identify the static level of the uppermost water-bearing zone underlying the Study Area. Reference to DWR Bulletin No. 104 suggests this upper aquifer is the Exposition Aquifer and will continue beyond the boundaries of the Site.

Water table elevation contours have been presented in previous reports based on water level measurements conducted on October 23, 1985 and July 27, 1986 (IT, Jan. 1986 and IT, Aug. 1986). In order to construct these contours, the water level was assumed to vary linearly between the measured points. The ground-water flow was toward the south to southwest in both months and varied generally by less than a foot between the two months. The hydraulic gradient was calculated as approximately 0.008 in both months.

The hydraulic gradient varied only slightly across the Site. No sink or recharge areas were indicated by the water level contours. Therefore, these contours indicate that the upper aquifer underlying the Site does not have abrupt lateral changes in transmissivity and does not access a lower aquifer under another pressure system.

2.3 CONCEPTUAL MODEL OF UPPER AQUIFER SYSTEM

The study and development of a Conceptual Model of the hydrogeology of the on-site upper aquifer system has involved the integration of the field data summarized in Sections 2.1 and 2.2. Three possible structures and behaviors of the upper aquifer were identified based on these data. Three Conceptual Models of the aquifer were constructed and included several necessary simplifying assumptions.

Mathematical Models based on these initial Conceptual Models were formulated. The behavior of these Mathematical Models was studied in comparison to the known behavior of the real upper aquifer system. The Conceptual Model most closely following the known behavior of the real aquifer system was identified based on these results. This model represents the most likely structure and behavior of the upper system.

Section 2.3.1 presents three Conceptual Models of the possible simplified structure and behavior of the upper aquifer system. Section 2.3.2 presents the mathematical analyses of these Conceptual Models. The Model which most closely follows the known behavior of the upper aquifer system is discussed in Section 2.3.3.

2.3.1 <u>Possible Structures and Behaviors</u>

As discussed in Sections 2.2.1 and 2.2.2, the stratigraphy of the Study Area is complex with changes in aquifer material both laterally and vertically. Aquifer tests indicate a large variation in transmissivity values and boundary effects are noted. The hydraulic gradient across the Site varies only slightly and does not indicate abrupt changes in hydraulic conductivity. Preliminary evaluation of these data sets has provided three possible Conceptual Models of the structure and behavior of the upper aquifer system within the Study Area. These Conceptual Models whose behavior will be analyzed mathematically, include:

- Conceptual Model No. 1

  A homogeneous aquifer system with constant values of aquifer thickness and hydraulic conductivity, vertically and horizontally across the Study Area

- Conceptual Model No. 2

  A heterogeneous aquifer system including significant variation in horizontal hydraulic conductivity and aquifer thickness across the Study Area

- Conceptual Model No. 3

  A heterogenous aquifer system with varying aquifer thickness and hydraulic conductivity changing vertically and horizontally across the Study Area

Conceptual Model No. 1 assumes that although there is a variation in the structures and properties of the upper aquifer, constant "mean" values of these parameters through space will best represent the behavior of the system as a whole. Conceptual Model No. 2 assumes the structures and properties of the upper aquifer vary significantly horizontally across the Study Area. The value of hydraulic conductivity is considered constant vertically in the aquifer. Figure 4 presents a mesh (isoparametric) of the transmissivity values across the Study Area based on Model No. 2. This figure is a "three-dimensional" representation of the relative magnitude of the transmissivity values across the Study Area by a mesh drawing.

Conceptual Model No. 3 also assumes the variation in the structures and properties of the upper aquifer is significant horizontally across the Study Area. The vertical properties of the aquifer also vary within this model. Figure 5 presents an isoparametric of the relative transmissivities of the upper aquifer of the Study Area with such a system. The effective horizontal hydraulic conductivity was used to calculate these transmissivities.

2.3.2 Mathematical Analyses of Upper Aquifer System

Mathematical Models were formulated which correlated to these previously described Conceptual Models. A computer-based Mathematical Model of two-dimensional ground-water flow and solute transport, called MOC (Konikow and Bredehoeft, 1984), was used to formulate and numerically solve the Models.

MOC is a well regarded ground-water flow and solute transport code which has been selected for this application for several reasons. MOC has been satisfactorally verified and methods for checking the numerical accuracy and precision of its solution have been established. The solution technique is unconditionally stable for ground-water flow and numerical oscillation is eliminated in the solution of the advective transport portion of the solute transport equation. The explicit procedure required to solve the remaining portions of the solute transport equation has three stability criteria, but the consequent time-step limitations are automatically determined by the program. Cost-effective analyses of this aquifer system were possible with application of this code.

A complete discussion of the derivation, assumptions, and limitations of Model MOC is presented in Appendix A. Conditions assumed when solving the flow equation which are of particular importance for this application include:

- The aquifer parameters (hydraulic conductivity, storage coefficient, effective porosity) are time invariant

- The flow is along a two-dimensional horizontal plane and gradients perpendicular to that plane are negligible

- The transmissivity of the aquifer does not vary with changes in the saturated thickness of the unconfined aqufier.

The numerical method (MOC) used to solve the Mathematical Models requires the Study Area be subdivided by a grid. MOC utilizes a rectangular, uniformly spaced, block centered finite difference grid which is presented in Figure 6. The grid varies incrementally by 175 feet in the east-west direction and 163 feet in the north-south direction.

The behavior of the Mathematical Models was compared to the behavior of the real aquifer system. This behavior included the steady state ground-water flow regime as established by the July 1986 water level measurements which varied by less than a foot from October 1985 measurements. The response of the real aquifer system and the Mathematical Model to the July 1986 pumping tests of wells MW-502 and MW-504 was also studied. Calculations based on average yearly rainfall for the Study Area indicate infiltration to the upper aquifer would have a negligible effect on this mathematical analyses and was disregarded.

A Mathematical Model of Conceptual Model No. 1 was initially formulated assuming a steady state flow regime with constant head boundary conditions established from the July 1986 water level measurements. The boundaries of the Model were located far enough from the areas of interest so as not to effect their behavior. This Model was simulated with a range of transmissivities from 2,000 to 5,000 gpd/ft constant across the Study Area. The aquifer thickness was assumed to be a constant 20 feet across the Study Area. Effective hydraulic conductivities were calculated based on the results of the July 1986 pump tests.

The simulated water levels of the steady state flow regime of this Model deviated less than one foot from the measured water levels of the real aquifer system. However, when the pump tests were simulated with this Model, the simulated drawdowns varied by as much as 10 feet from the measured drawdowns of the July 1986 pump test. Therefore, this Model is an unacceptable representation of the real aquifer system.

A Mathematical Model of Conceptual Model No. 2 was formulated assuming a steady state flow regime with boundary conditions established as described with Conceptual Model No. 1. Aquifer thicknesses were based on well logs and varied from 6 to 28 feet. The hydraulic conductivities were derived directly from the aquifer test results and a trending heterogeneity was assumed. In those wells whose pump tests exhibited a boundary effect, the first leg of the drawdown curve was assumed representative of the material immediately surrounding the pumped well. The hydraulic properties of the simulated aquifer were assumed constant with depth. The transmissivities of the Study Area resulting from this approach are presented in Figure 4.

The simulated steady state flow regime of the Model resulting from Conceptual Model No. 2 deviated significantly from the observed flow regime of the real upper aquifer system. The large changes in the hydraulic gradient across the Study Area in the simulated flow regime were the most notable difference between the two. When the July 1986 pump tests were simulated with this Model, the simulated drawdowns varied by as much as 7 feet from the measured values. Thus, Conceptual Model No. 2 was also an unacceptable representation of the real upper aquifer system.

A Mathematical Model of Conceptual Model No. 3 was formulated assuming a steady state flow regime with constant head boundary conditions established from the July 1986 water level measurements. Aquifer thicknesses were based on well logs and varied from 6 to 28 feet. The hydraulic conductivities were derived directly from the aquifer tests except when a boundary effect was observed. In these cases, significant vertical changes in the hydraulic conductivity of the aquifer were assumed. The "effective" hydraulic conductivity for parallel layers of differing hydraulic conductivity was then calculated based on the boring logs and the aquifer test results. The transmissivities of the Study Area resulting from this approach are presented in Figure 5.

The simulated water levels of the steady state flow regime of this Model generally deviated less than one half a foot from the measured water levels of the real aquifer system. When the July 1986 pump tests were simulated with the Mathematical Model of Conceptual Model No. 3, the simulated drawdowns were in agreement with the measured values. Therefore, Model No. 3 was accepted as the best representation of the real upper aquifer system at the Study Area.

2.3.3 Apparent Structure and Behavior of Upper Aquifer System

As presented in Section 2.3.2, mathematical analysis of the upper aquifer system indicates Conceptual Model No. 3 best represents its structure and behavior. Table 2 presents the hydrogeologic input parameters for the mathematical analysis (MOC) of Conceptual Model No. 3. Figure 7 presents an isoparametric mesh of the inputted aquifer thickness. As discussed previously, Figure 5 presents an isoparametric mesh of the resulting transmissivities. The water-level contours of the steady-state ground-water flow system resulting from this analyses are presented in Figure 8.

In summary, both field data and mathematical analyses of Conceptual Models indicate the upper aquifer system behaves as a heterogeneous system with the aquifer thickness varying from 6 to 28 feet across the Study Area. The results of this computer-based mathematical analysis indicates the hydraulic conductivity varies laterally across the Study Area. In the areas near monitoring wells MW-502 and MW-504 there are significant vertical changes in the hydraulic conductivity of the aquifer. These wells are perforated in zones of fine-grained sand, gravel, and cobbles. The effective hydraulic conductivity for parallel layers of differing properties was calculated for these regions. The mathematical analyses indicate these are representative values for an areal steady state analysis of the aquifer system.

As discussed previously in Section 2.2.1, the data available on the off-site region of the Study Area consists of several driller's well logs. No other data including water level measurements or aquifer tests were available for the off-site region of the Study Area. The off-site region was assumed of constant hydraulic conductivity with slight change in aquifer thickness. The hydraulic conductivity was derived from the aquifer test results of similar aquifer material on-site. Although insufficient data makes predictions in this off-site area difficult, modeling based on existing data does yield valuable information about its possible gross behavior.

Conceptual and Mathematical Model No. 3 best represents the ground-water flow system of the upper aquifer. Therefore, all subsequent numerical simulations of ground-water flow as described in the following sections were performed based on Conceptual and Mathematical Model No. 3.

3.0 SOLUTE MIGRATION PATTERNS OF UPPER AQUIFER

A discussion of the movement of dissolved hydrocarbon compounds from possible on-site surface sources to the ground water and the resulting migration of dissolved components in the upper aquifer is presented in this Section. The Conceptual/Mathematical Model No. 3 discussed in the previous Section was used in this analysis. An understanding of the possible sources of hydrocarbons and migration patterns of dissolved hydrocarbon in the soil and ground water of the Study Area was necessary for two reasons. First, the location of any possible future monitoring wells could be optimized. Secondly, the design of any interim remedial measures could be improved with this understanding.

The ground-water quality data collected to date were evaluated. The history of the Site was studied in order to determine possible sources of contamination. Three possible scenarios involving the movement of hydrocarbons into the upper aquifer system was studied. Mathematical Models were constructed of these scenarios and were analyzed both analytically and numerically (MOC).

The source history of the Site was discussed earlier in Section 1.2. The ground-water quality data is summarized in Section 3.1. Section 3.2 presents the mathematical analyses of three migration scenarios. A discussion of future monitoring well locations is presented in Section 3.3.

3.1 DISTRIBUTION OF HYDROCARBONS IN THE STUDY AREA

Soil samples have been collected from 11 soil borings and 14 monitoring wells at the Site. The soil samples were tested in the field for the presence of volatile organics using an Organic Vapor Analyzer (OVA). A select number of soil samples were analyzed in the laboratory for organic and inorganic constituents. The ground water from fourteen monitoring wells (Figure 2) perforated in the upper aquifer have been sampled for inorganic and organic contaminants in October 1985 and July 1986. A detailed discussion of the analytical results of the soil and ground-water samples and their interpretation have been presented in previous IT reports and progress reports. A summary of these results is presented in the following paragraphs of this Section.

Background levels of chemical constituents were established from the results of well MW-104. The chemical data at the Site indicated detectable concentrations of fuel hydrocarbons but no significant inorganic (metals) contamination.

Analyses of soil samples collected from the soil borings and monitoring wells at the Site revealed above background concentrations of oil-related volatile organic compounds at boring 301 and monitoring well locations MW-102, MW-201, and MW-204. The detected concentrations of benzene ranged from 5 to 390 micrograms per kilogram (μg/kg), with the highest concentration measured in samples from well MW-102. Based on the results of the monitoring of organic vapors at the Site, the southwest region appeared to have the greatest concentration of vapors.

The results of the ground-water quality program indicate contamination by fuel-related organic constituents. In July 1985, an apparent thickness of 0.01-inch of free product was recorded in well MW-102. No other monitoring well at the Site has shown any indication of free product.

During the October 1985 sampling, as presented in the January 1986 IT report, dissolved volatile organic compounds were detected in ground-water samples from the ten monitoring wells existing at that time. Benzene, toluene, ethylbenzene, and xylenes were detected at higher concentrations than other organic constituents. Benzene was detected in all monitoring wells ranging from a trace in the background well MW-104 to 4,600 and 8,400 micrograms per liter (μg/ℓ) in wells MW-206 and MW-102, respectively.

During the July 1986 sampling, as presented in the bimonthly progress report, benzene was detected in all fourteen monitoring wells except wells MW-104 and MW-201. Benzene concentrations ranged from a trace in well MW-103 to 8100 and 10,000 μg/L in wells MW-202 and MW-502, respectively.

3.2 ANALYSIS OF SOLUTE MIGRATION

3.2.1 Possible Sources of Fuel Hydrocarbons to Soil and Ground Water

In order to gain an understanding of the possible patterns of solute migration in the Study Area, the results of the organic chemical sampling program were studied in relation to the history of the Site. As discussed in previous reports, the source of hydrocarbons in the subsurface soil and ground water can only be examined in a general manner. In a refinery operating for more than forty years, it is difficult to determine the nature and quantify the possible amount of fuel hydrocarbons lost to the subsurface.

The probable primary transport mechanisms of chemicals to the ground water include downward migration of liquid organics and migration of the dissolved phase by infiltration of water through the soil pore space. Free hydrocarbons have not been observed in the monitoring wells, except well MW-102 which showed an apparent free product thickness of 0.01-inch in July 1986. This lack of a measurable amount of free product at the ground water free surface indicates that although movement of liquid organics to the water table may have been a transport process in the past, it is probably no longer operating to any significant extent.

Potential source areas of organic contamination to the ground-water system were studied based on the history of the Site (Section 1.2). Soil and water quality results have indicated these potential source areas fall into two general categories, as follows:

- Comparatively minor or no longer active source areas in which hydrocarbon contaminants no longer migrate to the ground-water system to any significant extent,

- Significant and potentially active source areas in which there has been a significant introduction of contaminants into the ground-water system.

Comparatively minor or no longer active sources of organic contamination to the ground-water system which may be identified include areas at the West and East Tank Farm.

However, water quality results in the West and East Tank Farm areas indicate liquid hydrocarbons are not currently moving to the water table to any significant degree. Also, based on the concentration of volatile organics in the soil samples of these areas, there is probably very limited movement of dissolved constituents into the ground-water from the unsaturated zone. The low concentrations of volatile organics in the ground-water of the West and East Tank Farm areas are probably the result of downward migration of dissolved constituents which in large part appears to have ceased for some time. For these reasons, movement of contaminants into the upper aquifer in the West and East Tank Farms was not analyzed further.

Soil samples from monitoring well MW-102 and MW-201, and ground-water samples from MW-102 and MW-504 have relatively high detected concentrations of dissolved hydrocarbon compounds. Based on the data collected to date, the 1963 gasoline spill and resulting fire in the area of MW-102 may be identified as the largest and most significant introduction of contaminants into the upper aquifer system. The possible movement of contaminants from this spill area into the upper aquifer has, therefore, been studied in detail. The following Sections present a conceptual and mathematical analysis of this possible movement of contaminants.

3.2.2 Mathematical Analysis of Solute Transport

As discussed previously, it is difficult to estimate the amount of downward migration of hydrocarbons at the Site from the vadose zone to the upper aquifer and to quantify the flux of solute into and out of the flow domain of the Study Area. Calibration of solute transport models to existing field data is impractical because of the lack of detailed understanding of the sources and hydrogeochemical processes acting over time at the Study Area.

Therefore, when mathematical analysis of the movement of solutes is desired, hypothetical scenarios involving the possible introduction and movement of organic contaminants are studied in order to understand the gross behavior of the system. Thus, calibration of solute transport simulations to actual field data is not attempted in this report.

Benzene was selected as the indicator parameter for evaluation and modeling for several reasons, as follows:

- Benzene has been observed in most of the monitoring wells at the Site with concentrations higher than other dissolved hydrocarbons,

- Benzene has a relatively high solubility compared to other gasoline constituents,

- Benzene is believed to be less adsorptive than other gasoline contituents, thus, is a good parameter for a conservative analysis of the extent of the plume.

Because higher concentrations of organic chemicals were found in soil and ground water in the area surrounding MW-102 and MW-504, a probable spill or leak in this area was examined as a likely source of contaminants to the ground water. As discussed previously, an accident was reported in 1963 in this area in which water and gasoline were ponded while gasoline was burning for several days. Initially, three possible scenarios involving the movement of benzene into the upper aquifer system as a result of the 1963 gasoline spill have been studied. These scenarios include:

- A "slug" of benzene introduced in the area of monitoring wells MW-504 and MW-102 which is allowed to migrate over a 23-year period (1963 to 1986),

- A constant source of benzene acting over a 23-year period introduced to the area near monitoring well MW-504 and MW-102,

- A constant source of benzene acting over a 10-year period introduced to the area near monitoring well MW-504. This resulting plume is then allowed to migrate an additional 13 years.

Mathematical models were constructed of these scenarios and were analyzed both analytically and numerically (MOC). These analyses have resulted in a better understanding of the possible plume migration patterns.

Initially, the possible migration of benzene was studied with a one dimensional analytical solute transport solution. This computer-based program, ODAST, considers advection and longitudinal dispersion in porous media with a steady state uniform flow field. A detailed discussion of this solution technique and program is presented in the American Geophysical Union's Water Resources Monograph 10 (AGU, 1984).

Additionally, numerical models were constructed of the three scenarios. Solute transport was studied with the ground-water flow model, MOC, developed and described in Section 2.3.3. The important assumptions and limitations made when solving the ground-water flow equation of MOC are presented in Section 2.3.2. A complete discussion of the derivation, assumptions and limitations of MOC is presented in Appendix A.

Important assumptions and conditions made when solving the solute transport equation include:

- Solute transport is dominated by advective transport, and, therefore, the two-dimensional areal solute transport equation may closely approximate a hyperbolic partial differential equation and be highly compatable with the method of characteristics solution technique

- No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties

- The aquifer is homogenous and isotropic with respect to the coefficients of longitudinal and transverse dispersivity.

The following Section presents the results of these analytical and numerical analyses.

3.2.3 Apparent Solute Migration Patterns

As discussed previously, numerical and analytical mathematical models were constructed of hypothetical scenarios involving the movement of benzene into the ground-water system based on the 1963 gasoline spill. These analyses indicate several probable behaviors of the transport of benzene in this ground-water system.

Numerical analyses of a spill incident in the area around wells MW-102 and MW-504 indicate this is a possible source location which would produce the plume pattern which has been detected in this area. However, calculations indicate no reasonable source concentration of benzene or amount of dispersion would have produced the dissolved hydrocarbon concentrations which have been detected in ground water at well MW-202, if the area around well MW-504 is considered the only source. Therefore, another subsurface source of benzene to the ground-water may exist near well MW-202. For instance, the spill incident of 1963 may have extended to areas near well MW-202.

Both analytical and numerical analyses of this spill indicate benzene did not migrate into the ground-water system as a slug-type source. One-dimensional analytical analyses (ODAST) of this spill incident were performed to indicate the percentage of the original source concentration present over 400-foot intervals downgradient from the source through time due to certain spill conditions. For instance, if benzene had entered the system as a discrete volume (slug) over a one year period in the mid-1960's, within five years of this period only approximately 14 percent of the original source concentration would be present 800 feet downgradient of well MW-504 (near the southern boundary of the Site). After 23 years, much less than 0.01 percent of the original source concentration would be present 800 feet down-gradient of well MW-504. Present concentrations of benzene in ground-water samples from this area indicate this is not the case.

Therefore, the soil in areas around MW-504 and MW-202 may have been acting as a source of contaminants to the ground-water system over an undetermined interval of time. Data on any possible off-site downgradient concentrations of benzene are required to estimate how long the soil in these areas may have been acting as a source. Preliminary calculations indicate these areas may have been acting as a source for at least ten years. This calculation is based on the assumption the 1963 gasoline spill was the surface incident which served as the primary source of this contamination.

In order to gain an understanding of the possible plume patterns within the Study Area, migration based on a range of source concentrations of benzene were simulated numerically with the MOC Model. A range of dispersion parameters were also simulated representing mild to moderate dispersion conditions. If two source areas are assumed to exist near wells MW-504 and MW-202, the results of these simulations indicate the maximum width of the plume may be between 1,300 and 1,600 feet approximately centered between wells MW-504 and MW-202. Water quality data collected to date is in agreement with these values.

The downgradient extent (if any) of the plume is difficult to estimate. This extent would be dependent on several factors including the source location and concentration, the interval of time that benzene has been introduced and migrated in the subsurface, the hydrogeologic properties of the off-site downgradient region, and the hydrochemical properties existing at the time of the migration of the benzene. Due to limited data collected to date on these factors, an analytical solution technique was used to calculate the downgradient extent (if any) of the plume.

For instance, an analytical solution was obtained with ODAST, assuming an equivalent hydraulic conductivity based on the results of the ground-water flow model presented in Section 2.3.3. Moderate longitudinal dispersion and a hydraulic gradient of 0.008 were assumed. The percentage of the original source concentration over time was solved for over 400 foot intervals down gradient from the source. If a constant source existing for approximately 10 years, is allowed to migrate another 13 years, less than 0.01 percent of the original concentration is estimated to be present 1,200 feet downgradient of the original source area (400 feet south of the southern boundary of the Site). If a constant source existing approximately 18 years, is allowed to migrate another 5 years, 61 percent of the original source concentration is calculated to be present at 800 feet and 0.8 percent of the original source concentration is calculated to be present 1,600 feet downgradient of the source area.

As previously discussed, these analyses are based on hypothetical source histories, as sufficient data does not exist to quantify the movement of solutes in the ground-water flow regime of the Study Area. Also, the analytical solution provides a rough initial estimate of the solute conditions at the Study Area. Simplifying assumptions necessary for this analytical solution (ODAST) include idealized hydrogeologic conditions and no spatial variation in the properties of the aquifer. However, these analyses did provide valuable information to aid in remedial action and to optimize the location of possible off-site monitoring wells.

The analyses presented in this Section have been areal and, therefore, assume constant vertical properties. The analyses of the hydrogeologic environment discussed in Section 2.0. indicate there are significant vertical changes in the aquifer material. Sand and gravel lenses of high hydraulic conductivity have been indicated. Thus, preferential movement of solutes along these channels may occur, but this differential movement is not considered with an analytical solution.

3.3 RECOMMENDED MONITORING WELL LOCATIONS AND FIELD PROGRAM

If the conditions assumed during the previously described solute migration analyses are reasonable, downgradient off-site migration of contaminants may have occurred. Therefore, two downgradient off-site monitoring wells in the upper aquifer are recommended to investigate the aquifer conditions in this area. The locations of these wells are based on the previous calculations presented in Sections 2.0 and 3.0.

One monitoring well is recommended to be located approximately 1,200 to 1,600 feet immediately south of well MW-504. If contaminants are observed at this location, a second well is recommended to be positioned approximately 1,200 feet immediately south of well MW-202. The proposed locations of these wells are presented in Figure 3.

4.0 INTERIM REMEDIAL MEASURES

The work plan developed by IT in April 1986 provided an initial screening of mitigation alternatives for controlling the movement of dissolved hydrocarbon constituents. The mitigation alternatives were analyzed based on engineering feasibility, environmental impact, time factors and cost effectiveness. Active physical containment by hydrodynamic control was initially identified as the most viable remedial alternative for this phase of the investigation.

Section 4.1 presents a discussion of the remedial measures recommended at this phase of the investigation. A numerical analyses with MOC (Section 2.0) of the proposed hydrodynamic control system is discussed in Section 4.2 and Section 4.3 presents recommended discharge plans for the extracted water. A field program to monitor the impact of these remedial measures is outlined in Section 4.4.

4.1 RECOMMENDED REMEDIAL MEASURES

At this phase of the investigation, recommended remedial measures should achieve two objectives, as follows:

- Remove sources of hydrocarbons to the ground water, and
- Contain the dissolved hydrocarbon plume to prevent off-site migration.

The following two sections present a discussion of remedial measures required to accomplish these objectives.

4.1.1 Remediation of Potential Source Areas

Initial analyses of possible solute migration patterns at the Site have identified two probable source areas of hydrocarbon constituents to the upper aquifer. These source areas include the unsaturated soil in the vicinity of wells MW-102, MW-504, and MW-202.

results, an interim remedial measure consisting of hydrodynamic control is recommended to isolate and stabilize the on-site plume and prevent any off-site migration of dissolved hydrocarbons in the upper aquifer. Hydrodynamic control is an active physical containment method which will isolate the on-site plume from the regional ground-water flow regime by means of pumping wells.

The hydrodynamic control method will consist of a line of pumping wells at the southernmost edge of the Site. This pumping system will serve as a subsurface hydraulic barrier in the upper aquifer at the downgradient edge of the Site. This pumping system was designed based on numerical analyses with the ground-water flow model, MOC previously developed and described in Section 2.3.3. Section 4.2 presents the results of these analyses plus the recommended pumping system. Section 4.3 presents the discharge plans being considered for the extracted water.

As discussed, this pumping system is recommended as an interim remedial measure. Additionally, a field program has been recommended in Sections 4.1.1 and 3.3 to investigate soil conditions and any possible off-site migration. Completion of the field and remedial program outlined in this report is recommended prior to the final design of effective long-term management practices.

4.2 ANALYSIS AND DESIGN OF PUMPING WELL SYSTEM

A pumping well system has been designed to control the on-site plume and, possibly, portions of any off-site plume. When in operation, the pumping well system will prevent possible off-site migration of contaminants. Design criteria for the pumping well system have included:

- A flexible system, easily constructed or dismantled,
- Pumping rates varied according to in situ conditions,
- Extraction locations and rates which prevent off-site migration of contaminants

The possible vertical and lateral extent of contamination in soil in the vicinity of wells MW-102, MW-504, and MW-202 is not currently known. Interpretation of available data including the analyses presented in Section 3.0 have indicated contamination of soil can be linked to contamination of the ground water beneath these areas. Therefore, soil mitigation should be considered as part of the plan of remedial actions. The vertical and lateral extent of contamination of soil in these areas must be known to develop an effective mitigation plan. Therefore, soil borings are recommended to be drilled in the areas of MW-202, MW-102, and MW-504 to assess the vertical and horizontal extent of soil contamination. The investigation methodology is as follows.

The boring pattern will be determined in the field starting from the center of the suspected contaminated area (between MW-102 and MW-202) and extending outward to the point where no indication of contamination is found. A total of 10 to 20 borings are predicted to be drilled.

The borings are expected to be drilled to a depth of 40 feet below ground surface. Soil samples will be collected every five feet and the borings will be logged by an IT field engineer or geologist. All samples recovered from the borings will be tested in the field by an Organic Vapor Analyzer (OVA) to test for the presence of volatile organic compounds in the soil. The results of the OVA analyses will be used to select one to three samples from each boring to be analyzed for oil and grease and benzene, ethylbenzene, toluene, xylene (BETX, EPA Method 8020). These two methods were selected because the previous investigation (IT report, January 1986) only showed elevated readings of oil and grease and BETX compounds in some of the soil samples analyzed.

4.1.2 Hydrodynamic Control of Plume

Field data, consisting of sets of water quality data, plus preliminary analytical and numerical analyses of possible solute migration patterns have indicated the likely extent of the plume. Aquifer tests and well logs have indicated rates and pathways of potential solute migration. Based on these

- Extraction rates optimized between plume control,and storage and treatment methods.

Analyses of the hydrogeology of the Study Area indicate the presence of sand and gravel lenses of relatively higher hydraulic conductivity. Preferential movement of solutes along these lenses may occur. This pumping program has also been designed to control any solute migration along known sand and gravel lenses near the southern boundary of the Site.

The design of the pumping system was optimized based on numerical analyses with the ground-water flow model, MOC, previously described and developed in Section 2.3.3. Numerous simulations of ground-water flow with the MOC Model were performed to develop optimal well locations and pumping rates to capture and prevent off-site migration of the on-site contaminant plume. Based on the results of these simulations, existing wells MW-502 and MW-501 are recommended as pumping wells extracting at rates of 20 gallons per minute (gpm) and 15 gpm, respectively.

The simulated water levels of this recommended program are presented in Figure 9. Hydraulic gradients indicate containment of the off-site plume including upgradient locations extending to wells MW-101 and MW-103. At the southern boundary of the Site, the capture zone extends approximately 900 feet to the west of well MW-502 and 600 feet to the east of well MW-501. The capture zone downgradient of wells MW-502 and MW-501 is limited to 200 feet.

In order to further test the effectiveness of this extraction program, migration of the on-site benzene plume over a six year period in response to well MW-502 and well MW-501 pumping at 20 and 15 gpm, respectively, was simulated. Benzene concentrations input into the MOC Model were based on the July 1986 water quality results. No potential constant sources of benzene from soil areas were considered and therefore, a "slug" source type was analyzed. Moderate dispersion parameters were assumed. The results of this simulation indicate containment of the on-site contaminant plume with over a 50 percent reduction in the original source concentration. The on-site contaminant plume did not migrate past the boundaries of the Site and its areal extent did not increase.

4.3 RECOMMENDED DISCHARGE PLANS

The ground water that will be extracted during the interim remedial program (about 50,000 gpd) can be managed through =56.46 a-f/yr

- Use of water for refinery purposes,
- Disposal of water into sanitary sewer system, or
- Treatment of water and use for refinery purposes or disposal into storm drain.

At this time, we believe that the most economical and effective way of managing the extracted water is by using it for desalting the crude oil at the refinery once the refinery operation starts. The resulting waste water of the desalting process will be disposed of in the industrial sewer under the current refinery permits.

4.4 RECOMMENDED FIELD PROGRAM

Due to the degree of heterogeneity of this aquifer system, the pumping rates optimized by the previously described numerical analyses may have to be varied according to in situ conditions. Water level data will be collected on a bi-weekly basis over the first two months of operation of the pumping system. This data will be used to verify the ground-water flow model and the efficiency of the resulting pumping system. The pumping program may be adapted to insure containment of the on-site plume. Verification of the ground-water flow model MOC will document the capture zone of the pumping system.

Ground-water samples will be obtained from all monitoring wells within the Study Area once this pumping system has reached a steady state condition. Numerical analysis with MOC indicate this aquifer system should reach a steady state condition within two months of operation of the pumping system. The results of these samples and the ongoing quarterly ground-water monitoring program are recommended to be analyzed to evaluate the effectiveness of this hydrodynamic control system.

5.0 SUMMARY AND CONCLUSIONS

A review was performed on all available field data collected in the Study Area. This data consisted of sets of water quality data and water level data plus the results of aquifer tests and well logs. Conceptual and Mathematical Modeling of the ground-water flow system based on this data has indicated the upper aquifer system behaves as a heterogeneous system with aquifer thickness varying from 6 to 28 feet across the Study Area. The hydraulic conductivity varies laterally across the Study Area. Also, in the area of wells MW-502 and MW-504, significant vertical changes in hydraulic conductivity were indicated.

The possible sources of contamination and patterns of solute migration were examined in the Study Area. Field data has indicated the 1963 gasoline spill incident in the vicinity of wells MW-504 and MW-102 may have been the most significant possible introduction of hydrocarbon contaminants into the upper aquifer. Conceptual and Mathematical Modeling of various hypothetical scenarios involving the movement of benzene into the upper aquifer based on the 1963 spill incident were performed.

These analyses indicate soil in the vicinity of wells MW-102, MW-504, and MW-202 may have been acting as a source of hydrocarbon contaminants over at least a ten year period. Based on this hypothesis, calculations with moderate values of dispersion indicate the maximum width of the plume may be between 1300 and 1600 feet approximately centered between wells MW-504 and MW-202. Both analytical and numerical analyses indicate off-site migration of hydrocarbon contaminants may have occurred to a distance of at least 400 to 800 feet south of the southern border of the Site. Two monitoring wells at these approximate off-site locations have been recommended in this report.

Interim remedial measures have been recommended in this report to remove potential sources of hydrocarbon constituents to the ground water and to contain the on-site contaminant plume in the upper aquifer to prevent off-site migration. The recommended remedial program to investigate soil conditions includes an assessment of the possible vertical and horizontal extent of contamination in soil in the vicinity of wells MW-102, MW-504, and MW-202 with a grid pattern of soil borings in this area.

In order to remediate ground-water conditions, a program of hydrodynamic control has been recommended to stabilize the on-site plume and prevent off-site migration of contaminants. This control system would consist of a line of pumping wells at the southernmost boundary of the Site. The design of this system was optimized based on numerical analyses with the Conceptual and Mathematical Model of ground-water flow discussed previously in this section. Existing wells MW-502 and MW-501 have been recommended as pumping wells extracting at rates of 20 gpm and 15 gpm, respectively. Due to the degree of heterogeneity of this aquifer, the pumping rates may have to be varied according to in situ conditions. A monitoring program to determine the effectiveness of this hydrodynamic control system has been outlined. Upon approval of this report, a work plan will be developed to enact these recommended actions.

Respectfully submitted,

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SM/EE/RM:djl

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TABLES

TABLE 1
RESULTS OF AQUIFER TEST ANALYSES

PUMPING WELL	TYPE OF ANALYSIS	PUMPING RATE (gpm)	TRANSMISSIVITY[a] (gpd/ft)	TRANSMISSIVITY[b] (gpd/ft)	TRANSMISSIVITY[c] (gpd/ft)	STORAGE COEFFICIENT
MW-101	Slug Test	-	918	-	-	-
MW-103	Slug Test	-	725	-	-	-
MW-201	Slug Test	-	4,068	-	-	-
MW-206	Slug Test	-	3,708	-	-	-
MW-502	Single Well	7.32	13,803	3,865	-	-
MW-503	Single Well	4.92	962	295	124	-
MW-504	Single Well	7.14	11,424	-	-	-
MW-504	Multiple Well	41.25	13,613	3,630	-	-
	Observation = MW-102		12,517	-	-	0.037 to 0.051

[a] Semilog plot of drawdown versus time resulted in more than one line with distinct slopes which decrease with time. This transmissivity was calculated based on the slope of the earliest time line (first leg).
[b] This transmissivity was calculated based on the slope of the second leg of the semilog plot, if this leg occurred.
[c] This transmissivity was calculated based on the slope of the third leg of the semilog plot, if this leg occurred.
[d] The dashed line (-) indicates calculation of this parameter was not appropriate for the type of aquifer test performed at this well.

TABLE 2
HYDROGEOLOGIC/SOLUTE TRANSPORT INPUT PARAMETERS FOR MOC MODEL APPLICATION [a,b]

DESCRIPTION	VALUE	UNIT
GRID DESCRIPTIONS:		
Number of Columns	22	-
Number of Rows	30	-
X-Distance	175	feet
Y-Distance	163	feet
HYDROLOGIC AND CHEMICAL PARAMETERS:		
Effective Porosity	0.20 to 0.30	-
Longitudinal Dispersivity	10 to 100	feet
Transverse Dispersivity	10 to 30	feet
Retardation Factor	1.0 to 2.5	-
Ratio of YY to XX Transmissivity	1.0	-

(a) Transmissivities and Aquifer thickness are presented in Figures 5 and 7, respectively.

(b) All ground-water flow analyses were steady-state, therefore, no specific yield was assigned.

FIGURES

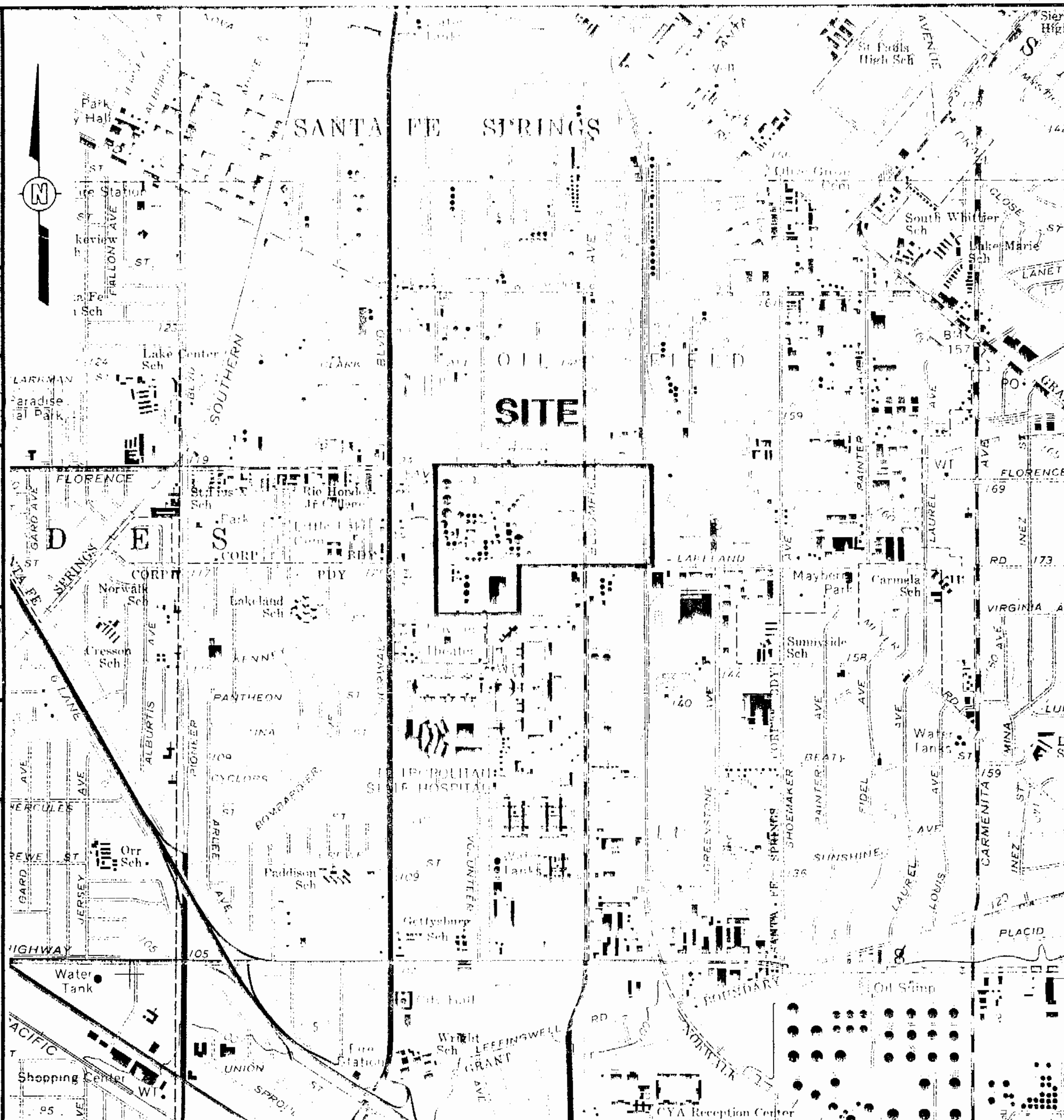
DRAWING NUMBER 850009-A1

CHECKED BY

APPROVED BY

MPS 11-1-85

DRAWN BY



SCALE

0 2000 4000 FEET

FIGURE 1

SITE VICINITY MAP

PREPARED FOR

POWERINE OIL COMPANY
SANTA FE SPRINGS, CALIFORNIA

IT ... Creating a Safer Tomorrow

REFERENCE:

7.5 MINUTE USGS TOPOGRAPHIC MAP OF WHITTIER, CALIFORNIA, QUADRANGLE

DATE:1965, PHOTO REVISED 1981

SCALE: 1" 2000'

85380

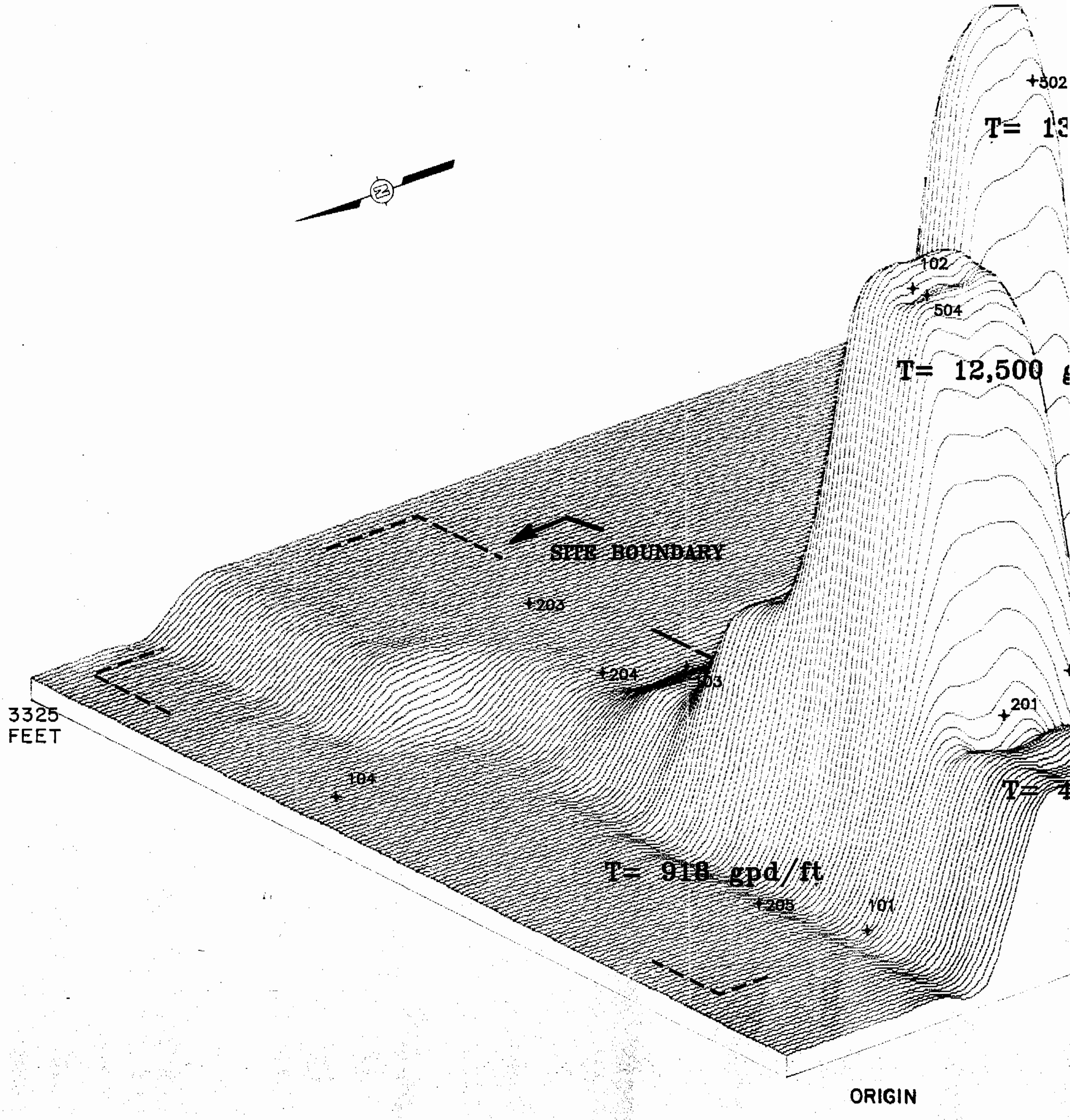
Do Not Scale This Drawing

FX-9 Wells

FX-9 Wells

FX-9 Wells

FX-9 Wells



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CHECKED BY	1-5-87
APPROVED BY	1-5-87
DRAWING NUMBER	850009-B16

122293

"Do Not Scale This Drawing"

NOTES:

1) MESH VIEWING ANGLES
   ROTATION OF AZIMUTH = 320°
   ELEVATION ANGLE = 40°

2) CALIBRATION ATTEMPTS PROVED THIS MODEL WAS UNACCEPTABLE (SECTION 2.3.2)

LEGEND:

+ 205 WATER MONITORING WELL

CORNERS OF SITE BOUNDRY

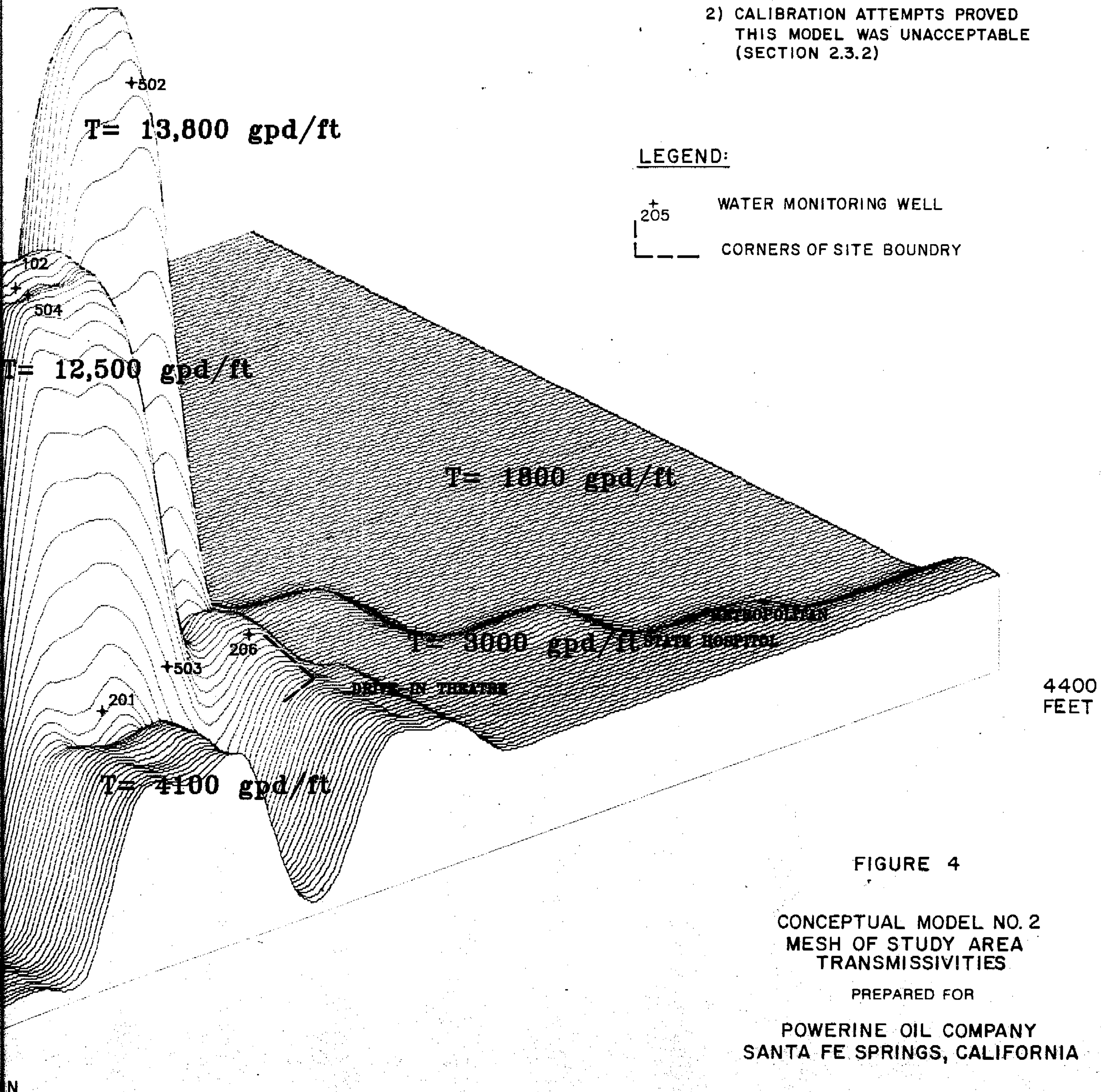

FIGURE 4

CONCEPTUAL MODEL NO. 2
MESH OF STUDY AREA TRANSMISSIVITIES

PREPARED FOR

POWERINE OIL COMPANY
SANTA FE SPRINGS, CALIFORNIA

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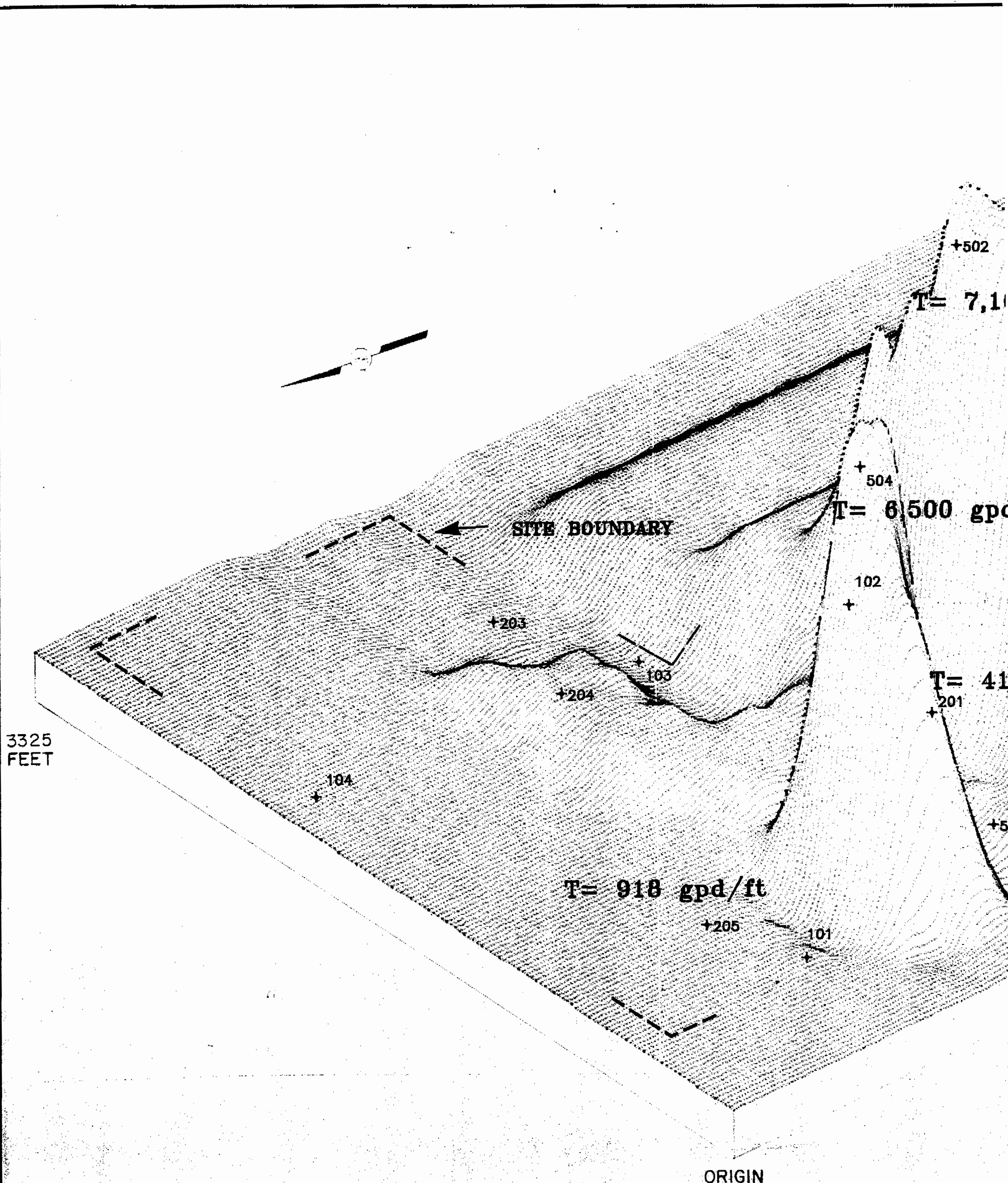
DRAWN BY BJW 1-2-87 | CHECKED BY | APPROVED BY | DRAWING NUMBER 850009-B17



122293

"Do Not Scale This Drawing"

NOTES:

1) MESH VIEWING ANGLES

ROTATION OF AZIMUTH = 320°

ELEVATION ANGLE = 55°

2) CALIBRATION PROCESS PROVED THIS MODEL WAS ACCEPTABLE (SECTION 2.3.3.)

LEGEND:

+ 205 WATER MONITORING WELL

CORNERS OF SITE BOUNDRY

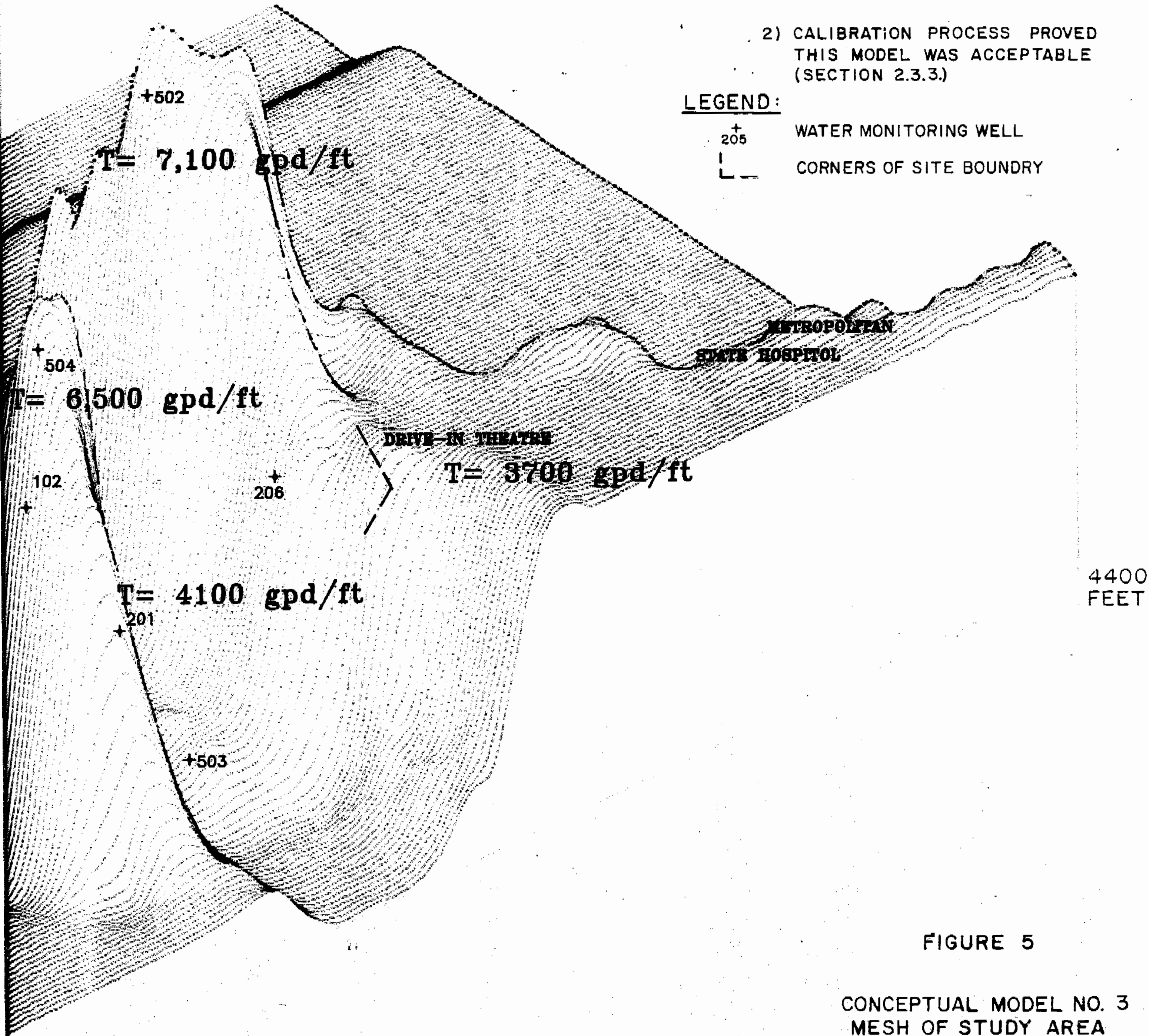


FIGURE 5

CONCEPTUAL MODEL NO. 3
MESH OF STUDY AREA
TRANSMISSIVITIES

PREPARED FOR

POWERINE OIL COMPANY
SANTA FE SPRINGS, CALIFORNIA

IT ... Creating a Safer Tomorrow

FX-9 Wells

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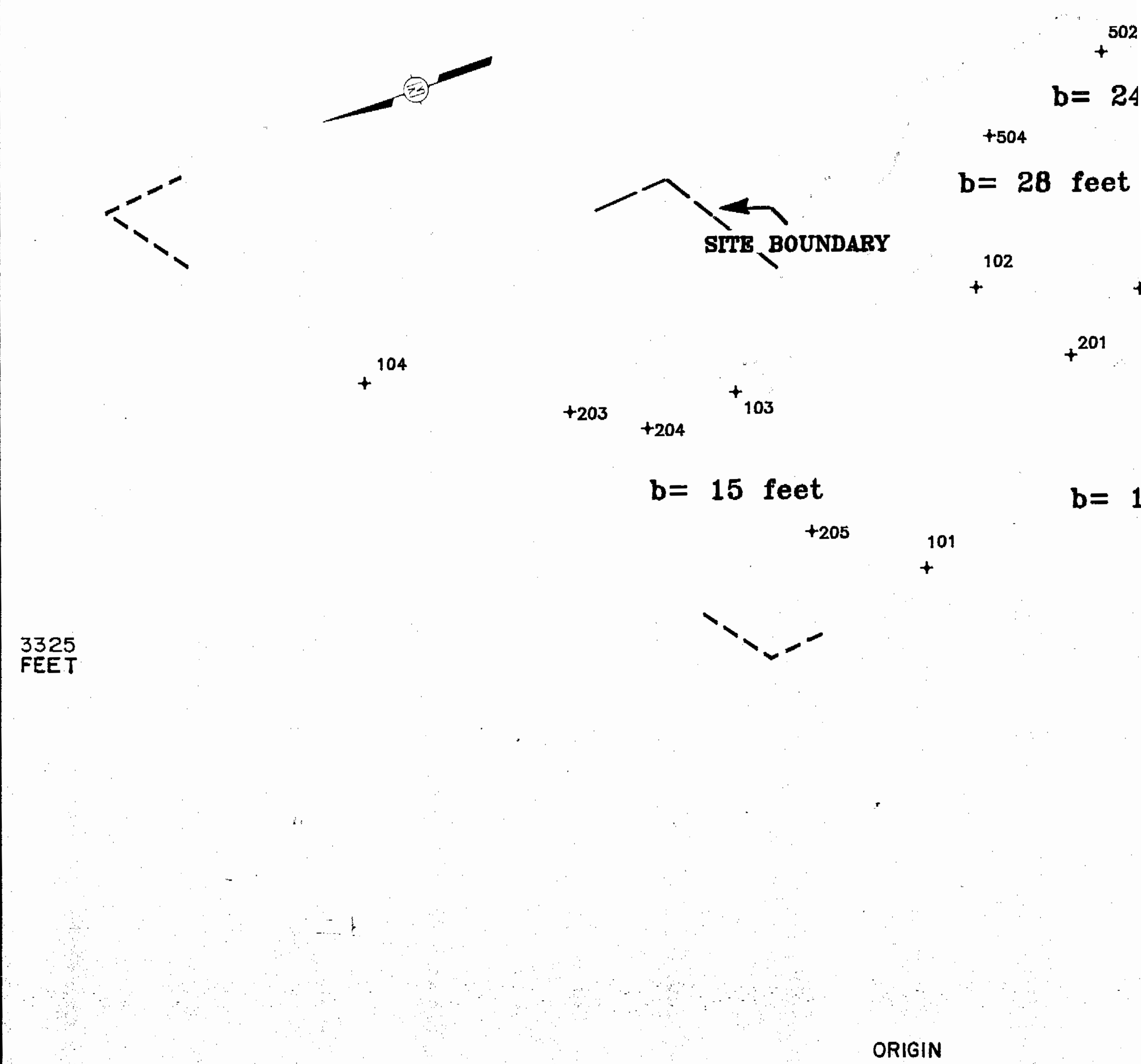


DRAWN BY BJW 1-2-87
CHECKED BY
APPROVED BY 1-5-87
DRAWING NUMBER 850009-B19

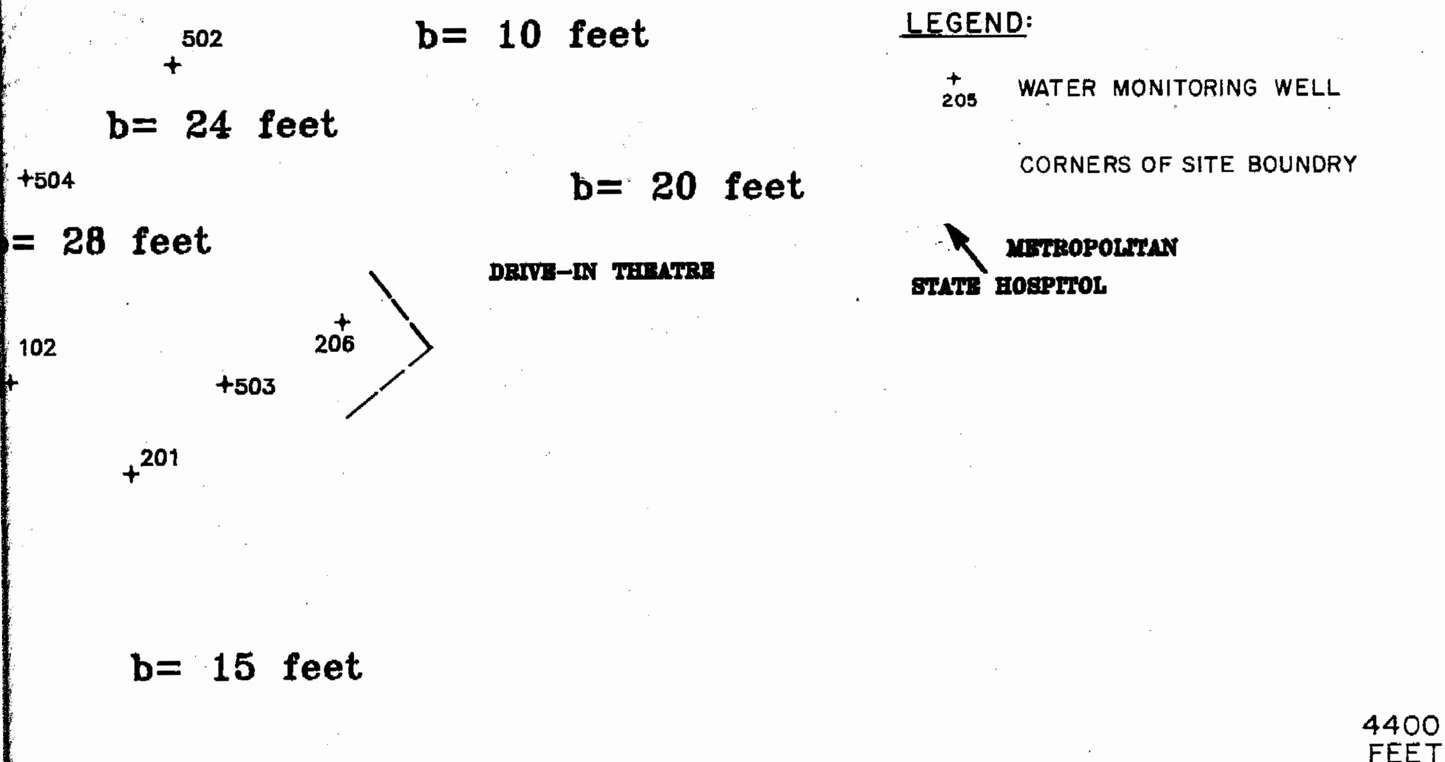
"Do Not Scale This Drawing"

122293

NOTES:

1) MESH VIEWING ANGLES
   ROTATION OF AZIMUTH = 320°
   ELEVATION ANGLE = 55°

2) b = AQUIFER THICKNESS



LEGEND:

+ 205 WATER MONITORING WELL

CORNERS OF SITE BOUNDRY

FIGURE 7

CONCEPTUAL MODEL NO. 3
MESH OF STUDY AREA
AQUIFER THICKNESS

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APPENDIX A

APPENDIX A
THEORETICAL BACKROUND AND FEATURES OF THE METHOD-OF-CHARACTERISTICS (MOC) MODEL FOR SOLUTE TRANSPORT

1.0 INTRODUCTION

The Method-of-Characteristics Model (MOC) is a numerical model developed by the U.S. Geological Survey to simulate two-dimensional ground-water flow and solute transport in confined, semi-confined, or unconfined (water table) aquifers (Konikow and Bredehoeft, 1984). The model computes the hydraulic head distribution in the aquifer and describes the chemical concentration in the aquifer system. The program developed to solve the ground-water flow and solute transport equations of the model is written in FORTRAN IV and is compatable with the IBM AT personal computer. This appendix includes a detailed description of the governing equations of ground-water flow and solute transport applied by the model as well as the assumptions associated with these equations. A description of the numerical methods used to solve these equations is also included.

2.0 THEORETICAL BACKGROUND

The numerical model MOC solves two simultaneous partial differential equations including the ground-water flow equation and the solute transport equation. The model can be applied to both steady-state and transient flow problems.

2.1 GOVERNING EQUATIONS OF GROUND-WATER FLOW

The following main assumptions and conditions are made when solving the flow equation:

- Darcy's law is valid and hydraulic-head gradients are the only significant driving mechanism
- The fluid (ground water) is homogenous and slightly compressible

- Gradients of fluid density, viscosity and temperature do not affect the velocity distribution

- The aquifer parameters (hydraulic conductivity, storage coefficient, effective porosity) are time invariant

- The flow is along a two-dimensional plane which may be vertical or horizontal and gradients perpendicular to that plane are negligible

- Changes in ground-water storage occur instantly with changes in hydraulic head

- The effective porosity and storage coefficient are constant in space

- The transmissivity of the aquifer does not vary with changes in the saturated thickness of an unconfined aquifer.

The partial differential equation (Pinder and Bredehoeft, 1968) governing the transient two-dimensional ground-water flow in a heterogenous, anisotropic, confined aquifer system written in Cartesian tensor notation is

$$\frac{\partial}{\partial x_i}\left(T_{ij}\frac{\partial h}{\partial x_j}\right) = S\frac{\partial h}{\partial t} + W \qquad i,j=1,2 \qquad (1)$$

where

T_{ij} = transmissivity tensor, L^2/T

h = hydraulic head, L

S = storage coefficient (dimensionless)

t = time, T

W = W (x,y,t) is the volume flux per unit area (positive sign for outflow), L/T

x_i and x_j = Cartesian coordinates, L

If fluxes of (1) direct withdrawal or recharge, such as well pumpage, well injection, or evapotranspiration, and (2) steady leakage into or out of the aquifer through a confining layer, stream bed, or lake bed are considered, then W (x,y,t) may be expressed as:

$$W(x,y,t) = Q(x,y,t) - \frac{K_z}{m}(H_s - h) \qquad (2)$$

where:

- Q = the rate of withdrawal or recharge, L/T
- K_z = vertical hydraulic conductivity of the confining layer, stream bed, or lake bed, L/T
- m = thickness of the confining layer, stream bed, or lake bed, L
- H_s = hydraulic head in the source bed, stream, or lake, L

The average pore water velocity of ground water as derived from Darcy's law can be written in Cartesian tensor notation as

$$v_i = -\frac{K_{ij}}{\varepsilon}\frac{\partial h}{\partial x_j} \qquad (3)$$

where

- v_i = pore water velocity in the direction of x_i, L/T
- K_{ij} = hydraulic conductivity tensor, L/T
- ε = effective porosity of the aquifer, dimensionless

2.2 GOVERNING EQUATIONS OF SOLUTE TRANSPORT

The following main assumptions and conditions are made when solving the solute transport equation:

- No chemical reactions occur that affect the concentration of the solute, the fluid properties, or the aquifer properties
- Ionic and molecular diffusion are negligible contributors to the total dispersive flux
- The aquifer is homogenous and isotropic with respect to the coefficients of longitudinal and transverse dispersivity.

The equation used to describe the two-dimensional areal transport and dispersion of a given nonreactive dissolved chemical species in flowing ground water was derived by Reddell and Sunada (1970), Bear (1972), Bredehoeft and Pinder (1973), and Konikow and Grove (1977). The equation may be written as:

$$\frac{\partial (Cb)}{\partial t} = \frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - \frac{\partial}{\partial x_i}(bCv_i) - \frac{C'W}{\varepsilon} \qquad (4)$$

where

C = concentration of the dissolved chemical species, M/L^3

D_{ij} = coefficient of hydrodynamic dispersion, L^2/T

b = saturated thickness of the aquifer, L

C' = concentration of the dissolved chemical in a source or sink fluid, M/L^3

The dispersion coefficient (Scheidegger, 1961), may be related to the velocity of ground-water flow and to the nature of the aquifer. The components of the dispersion coefficient for two-dimensional flow in an isotropic aquifer may be stated explicitly as:

$$D_{xx} = D_L \frac{(v_x)^2}{|v|^2} + D_T \frac{(v_y)^2}{|v|^2} \qquad (5)$$

$$D_{yy} = D_T \frac{(v_x)^2}{|v|^2} + \frac{(v_y)^2}{|v|^2} \qquad (6)$$

$$D_{xy} = D_{yx} = (D_L - D_T) \frac{v_x v_y}{|v|^2} \qquad (7)$$

3.0 NUMERICAL METHODS

3.1 FLOW EQUATION

A numerical solution to equation (1) can be obtained by substituting finite-difference approximations for the differential forms. The differentials ∂x_i and ∂x_j are approximated by finite lengths, Δx and Δy. The differential ∂t is approximated by a finite time period Δt. The aquifer is subdivided (discretized) into finite volumes having dimensions $m\Delta x\Delta y$ with transmissivity varying from volume to volume (Walton, 1984). A grid is superposed over the map of the ground-water system with the areas of the grid $\Delta x\Delta y$ small compared with the areal extent of the ground-water system. MOC utilizes a rectangular, uniformly spaced, block-centered finite difference grid.

If the coordinate axes are alined with the principal directions of the transmissivity tensor, equation (1) may be approximated by the following implicit finite difference equation:

$$T_{xx[i-\frac{1}{2},j]} \left[\frac{h_{i-1,j,k} - h_{i,j,k}}{(\Delta x)^2} \right] + T_{xx[i+\frac{1}{2},j]} \left[\frac{h_{i+1,j,k} - h_{i,j,k}}{(\Delta x)^2} \right]$$

$$+ T_{yy[i,j-\frac{1}{2}]} \left[\frac{h_{i,j-1,k} - h_{i,j,k}}{(\Delta y)^2} \right] + T_{yy[i,j+\frac{1}{2}]} \left[\frac{h_{i,j+1,k} - h_{i,j,k}}{(\Delta y)^2} \right]$$

$$= S \left[\frac{h_{i,j,k} - h_{i,j,k-1}}{\Delta t} \right] + \frac{q_{w(i,j)}}{\Delta x \Delta y} \frac{K_z}{m} \left[H_{s(i,j)} - h_{i,j,k} \right] \qquad (8)$$

where

i,j,k	=	indices in the x,y and time dimensions, respectively
$\Delta x,\Delta y,\Delta t$ =	=	increments in x, y and time dimensions, respectively
q_w	=	volumetric rate of withdrawal or recharge at the (i,j) node, L^3/T

The finite difference equation (8) is solved numerically for each node in the grid using an iterative alternating-direction implicit (ADI) procedure.

3.2 SOLUTE TRANSPORT EQUATION

The method of characteristics is used to solve the solute transport equation. This approach is valid if solute transport is dominated by advective transport, as is common in many field-problems. With this method, equation (4) is not solved directly, but rather, an equivalent system of ordinary differential equations is solved. The form of the solute transport equation that is solved by MOC is, as follows:

$$\frac{\partial C}{\partial t} = \frac{1}{b}\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) - V_i\frac{\partial C}{\partial x_i} + \frac{C\left(S\frac{\partial h}{\partial t} + W - \varepsilon\frac{\partial b}{\partial t}\right) - C'W}{\varepsilon b} \qquad (9)$$

This method uses a particle-tracking procedure to represent advective transport. The changes in concentration caused by hydrodynamic dispersion, fluid sources, divergence of velocity, and changes in saturated thickness are calculated using a two-step explicit procedure to solve a finite difference approximation to the equation:

$$\Delta C_{i,j,k} = \Delta t\left[\,1/b\,\frac{\partial}{\partial x_i}\left(bD_{ij}\frac{\partial C}{\partial x_j}\right) + F\,\right] \qquad (10)$$

where $$F = \frac{C\left(S\frac{\partial h}{\partial t} + W - \varepsilon\frac{\partial b}{\partial t}\right) - C'W}{\varepsilon b} \qquad (11)$$

3.3 STABILITY CRITERIA AND NUMERICAL ACCURACY

The numerical solution technique used to solve the ground-water flow equation is unconditionally stable. However, the two-step explicit procedure used to solve the finite difference equation that describes the effects of hydrodynamic dispersion, fluid sources, and sinks, and divergence of velocity has several stability criteria. These criteria may require that the time step used to solve the flow equation be subdivided into a number of smaller time increments to accurately solve the solute-transport equation. These consequence time-step limitations are automatically determined by the program MOC.

Mass balance calculations are performed after specified time increments to help check the numerical accuracy and precision of the solution. The principal of conservation of mass requires that the cumulative sums of mass inflows and outflows (or net flux) must equal the accumulation of mass (or change in mass stored). The difference between the net flux and the mass accumulation is one measure of the numerical accuracy of the solution.

3.4 BOUNDARY AND INITIAL CONDITIONS

Obtaining a solution to the equations that describe ground-water flow and solute transport requires the specification of boundary and initial conditions. If variables in the governing partial differential equation are time-dependent, the initial condition(s) prescribed by the physical situation at the initial time (t=0) should be specified. Initial conditions may also be specified at the start of a simulation so that water levels will change during the simulation not only in response to a new stress, but also to the initial condition.

Two general types of boundary conditions including constant-head and constant-flux are incorporated in MOC. These boundaries can be used to represent the real boundaries of an aquifer as well as to represent artificial boundaries for the model. A constant head boundary is defined as a line along which there is no change in water levels over time. This boundary type can be used to represent recharge boundaries or areas beyond the influence of hydraulic stresses. A constant-flux boundary may be defined as a barrier boundary across which ground-water flow has a constant finite value. The boundary can be used to represent aquifer underflow, well withdrawals, or well injection. A no-flow boundary is a special case of a constant-flux boundary.

If a constant-flux or constant-head boundary represents a fluid source, then the chemical concentration in the source fluid (C') must also be specified. If the boundary represents a fluid sink, then the concentration of the produced fluid will equal the concentration in the aquifer at the location of the sink.

4.0 PROGRAM VERIFICATION

MOC is a ground-water flow and solute transport code first developed in 1978 by L. F. Konikow and J. D. Bredehoeft of the U.S. Geological Survey (USGS). The User's Manual is published by the USGS (Konikow and Bredehoeft, 1984) and presents the formal verification process of the model. As presented in the manual, the results of analytical analyses of relatively simple problems were in good agreement with the numerical solutions obtained from MOC. The user is cautioned that, in some cases, the accuracy and efficiency of the model application can be significantly affected by the selection of values for cetain user-specified options. Therefore, the accuracy and precision of each application should be evaluated by computing the magnitude of error in the mass balance which should generally be less than 10 percent (Konikow and Bredehoeft, 1984). These calculations are performed and outputted by the model.

MOC has been recently checked and distributed by the International Ground Water Modeling Center. Several published papers have included discussions of the application of MOC to both field and research problems. This numerical model has often been used in classroom work and is widely accepted.

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